

# Measurement of transient gas flow parameters by diode laser absorption spectroscopy

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**Abstract.** An absorption spectrometer based on diode lasers is developed for measuring two-dimension maps of temperature and water vapour concentration distributions in the combustion zones of two mixing supersonic flows of fuel and oxidiser in the single run regime. The method of measuring parameters of hot combustion zones is based on detection of transient spectra of water vapour absorption. The design of the spectrometer considerably reduces the influence of water vapour absorption along the path of a sensing laser beam outside the burning chamber. The optical scheme is developed, capable of matching measurement results in different runs of mixture burning. A new algorithm is suggested for obtaining information about the mixture temperature by constructing the correlation functions of the experimental spectrum with those simulated from databases. A two-dimensional map of temperature distribution in a test chamber is obtained for the first time under the conditions of plasma-induced combustion of the ethylene–air mixture.

**Keywords:** absorption spectroscopy, diode laser, gas flow probing, measurements of temperature and concentration.

## 1. Introduction

The method of diode laser absorption spectroscopy (DLAS) is widely used for detecting parameters of combustion zones in transient gas flows [1, 2]. The method is often employed not only for measuring the temperature and partial pressures of combustion components [3–5], but also for investigating channels of gas-cycle chemical reactions [2]. Data obtained by DLAS yield important information that is used for developing and improving constructions of modern engines [6–9]. The difficulty of measuring parameters of combustion zones by DLAS is related to both the transient combustion in the flows of fuel and oxidiser and to the considerable inhomogeneity of chemical reaction zones caused by a turbulent character of component mixing under direct fuel injection from the wall.

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A particular DLAS realisation depends on the combustion zone parameters among which the main is a total pressure of the mixture. In cases where combustion occurs at pressures lower than 1 atm, the linewidths of test molecules are sufficiently small and, as a rule, one may select either isolated or slightly overlapping absorption lines. Water molecule is often chosen as a test one because H<sub>2</sub>O is a final combustion product of hydrocarbon components of fuel and there are commercially available diode lasers operating in the spectral bands where water absorption lines reside. The concentration of water vapours at final stages of combustion is used to determine the efficiency of fuel burning.

There are various modifications of the DLAS method for specific problems. If a test molecule has sufficiently strong absorption lines, the direct absorption measurement is used, which is specific in simple interpretation of measurement results [3, 5]. In temperature measurements, the absorption is detected in the lines of a test molecule differing in the position of the lower rovibrational level. In the case of comparatively slow processes and high concentrations of components one can assume that the medium is in thermodynamic equilibrium and the populations of levels obey the Boltzmann distribution. The gas temperature is determined either from the ratio of absorption coefficient amplitudes or, more precisely, from the ratio of integrals over entire line profiles.

Diagnostics of combustion processes in high-velocity flows requires measurements of parameters in a combustion zone under transient conditions. The characteristic time scale of density and temperature variations in such flows is 10<sup>-5</sup> s, which requires the duration of absorption measurement on the order of dozens of microseconds. Estimates indicate that if the thickness of the investigated combustion zone is 1–10 cm then at the pressure  $P = 0.1–1$  atm the relative variation in the probe beam intensity should be sufficiently low:  $\Delta I/I_0 \sim 10^{-3}$ .

In previous papers we reported the development of DLAS for determining temperature and partial pressure of water vapours in various parts of the combustion zone in mixing supersonic flows of fuel (hydrogen or ethylene) and oxidiser (air) [10, 11]. The method efficiency has been demonstrated under sufficiently hard conditions of diagnosing the gas mixture on the IADT-50 supersonic combustor at the Joint Institute for High Temperatures, Russian Academy of Sciences.

Serious problems in these experiments were substantially low reproducibility of detailed parameter distributions in the combustion zone from run to run and absorption of probe laser radiation in laboratory air along the optical path outside the test chamber. The first factor hindered comparison of measurement results in different runs. The second factor resulted in that a detected absorption spectrum of water

vapour was the superposition of sufficiently narrow absorption lines of water vapour at the pressure of 150–400 Torr inside the test chamber and wider lines of water vapour at the atmosphere pressure outside the chamber. The superimposed spectra substantially complicated processing of experimental data and increased the error in determining gas mixture parameters.

At a next stage, the method for detecting the spatial temperature profile in a working chamber had to be developed because the profile information is very important for improving the design of the combustor and geometry of electrodes of the plasma generator.

The present work is aimed at developing a new version of DLAS capable of taking two-dimension (along and across the gas flow) measurements of the spatial distribution of parameters in the transient combustion zone under the conditions of single test runs of the combustor. To this end, the optical scheme of the spectrometer was substantially modified and the system was developed for taking into account variations in the combustion parameters from run to run. In addition, the hardware differential scheme was suggested and realised, which reduced the influence of atmospheric water on the absorption signal. In the process of modification, the systems for controlling the diode laser and for digital recording analytical signals have been totally altered, and a new algorithm for calculating medium parameters while processing transient absorption spectra has been developed.

## 2. Basic relations

Light propagation through an absorbing medium is described by the Bouguer–Lambert law, which in the case of weak absorption takes the form

$$I(\nu) \approx I_0(\nu) - I_0(\nu) \sum_i \int_0^L S_i(T) g_i(\nu, T, P, n) n(y) dy. \quad (1)$$

Here,  $I(\nu)$  ( $\text{W cm}^{-2}$ ) is the intensity of the monochromatic radiation of frequency  $\nu$  ( $\text{cm}^{-1}$ ) after it has covered the distance  $L$  (cm) inside object;  $I_0(\nu)$  is the intensity of the incident monochromatic radiation of frequency  $\nu$ ;  $S_i$  ( $\text{cm mol}^{-1}$ ) is the integrated intensity of  $i$ th line;  $g_i(\nu)$  (cm) is the absorption line profile;  $n(y)$  is the concentration of absorbing molecules ( $\text{mol cm}^{-3}$ ); and  $P$  (atm) is the total pressure of the mixture. By the integrated intensity we mean the integrated absorption coefficient per single molecule. The integrated intensity of the line depends on temperature  $T$  (K), and the line profile depends on temperature, pressure and gas mixture composition and is determined by the broadening mechanisms.

In the case of uniform temperature and concentration distributions along the probe beam, the absorption spectrum has the form

$$A(\nu) \approx \frac{I_0(\nu) - I(\nu)}{I_0(\nu)} = \sum_i S_i(T) g_i(\nu, T, P, n) nL. \quad (2)$$

At pressures not noticeably differing from atmospheric pressure the spectral line profile  $g(\nu - \nu_0)$  is conventionally given by the Voigt profile. In diagnosing gas flows and flames a typical full-width at half-maximum (FWHM) of the absorption line under investigation is  $\sim 0.01$ – $0.1 \text{ cm}^{-1}$  (0.3–3 GHz); hence, single-mode (single-frequency) diode lasers (DLs) with the line FWHM of  $\sim 10$ – $50 \text{ MHz}$  can be considered monochromatic so that Eqns (1) and (2) ensure high accuracy in interpreting absorption measurements.

The dependence of the line strength on temperature is determined by the formula

$$S(T) = S(T_0) \frac{Q(T_0)}{Q(T)} \times \exp \left[ -\frac{hcE''}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \left[ \frac{1 - \exp(hc\nu/kT)}{1 - \exp(hc\nu/kT_0)} \right], \quad (3)$$

where  $Q(T)$  is the partition function that only depends on temperature; and  $E''$  ( $\text{cm}^{-1}$ ) is the energy of the lower quantum state from which the transition originates.

The ratio of strengths of two lines is the single-valued function of temperature [in (3) we neglect the deviation of the expression in second brackets from unity] that is independent of the concentration of absorbing particles:

$$R = \left( \frac{S_1}{S_2} \right)_T = \left( \frac{S_1}{S_2} \right)_{T_0} \exp \left[ -\frac{hc\Delta E}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right], \quad (4)$$

where  $S_1$  and  $S_2$  are the line strengths at certain temperature  $T_0$ ; and  $\Delta E$  is the ‘energy gap’ between the chosen states. Thus, simultaneous measurements of the integrated absorption in two lines can be used for determining the temperature in a probed volume, and from the absolute value of absorption for a line with known spectroscopic parameters one can calculate the absorbing component concentration.

The line strengths for many transitions of simple molecules at room temperature have been determined and loaded to databases (HITRAN [12], HITEMP [13] and SPECTRA [14]). For an arbitrary temperature, the line strength  $S(T)$  can be calculated according to (3).

The experiments in the present work have been performed with the  $\text{H}_2\text{O}$  absorption lines having the frequencies:  $7189.200 \text{ cm}^{-1}$  ( $E'' = 1395 \text{ cm}^{-1}$ ),  $7189.344 \text{ cm}^{-1}$  ( $E'' = 142 \text{ cm}^{-1}$ ),  $7189.541 \text{ cm}^{-1}$  ( $E'' = 1255 \text{ cm}^{-1}$ ),  $7189.715 \text{ cm}^{-1}$  ( $E'' = 2005 \text{ cm}^{-1}$ ). The choice of these lines is explained by a noticeable difference in the positions of lower levels of the transitions and by the possibility of their recording in a single scan of the diode laser ( $\sim 1 \text{ cm}^{-1}$ ), which is principally important in measurements of the object temperature.

## 3. Experimental installation

A thorough description of the DLAS-spectrometer structure and design of its main units is given in [10]. Here we only present a general scheme of the modified DLAS-spectrometer and describe in more details the units subjected to substantial modernisation.

### 3.1. Optical scheme

The optical scheme of the device is presented in Fig. 1. Radiation from the DL passes through a single-mode optical fibre to the first multiplexer, in which it is split into two channels with the intensity ratio of 60%:40%. In the first channel, radiation passes to optical units mounted on the input flange of the measuring chamber; in the second channel radiation passes to a reference channel (its purpose and description are given below). Radiation directed to the chamber is split by a second multiplexer into two channels with the intensity ratio of 50%:50%. In one channel (signal) radiation passes to the movable optical unit that can move in two coordinates; in the second channel (reference) radiation passes to the optical unit mounted at a certain position on the chamber. Radiation in the signal and reference channels is collimated by gradient

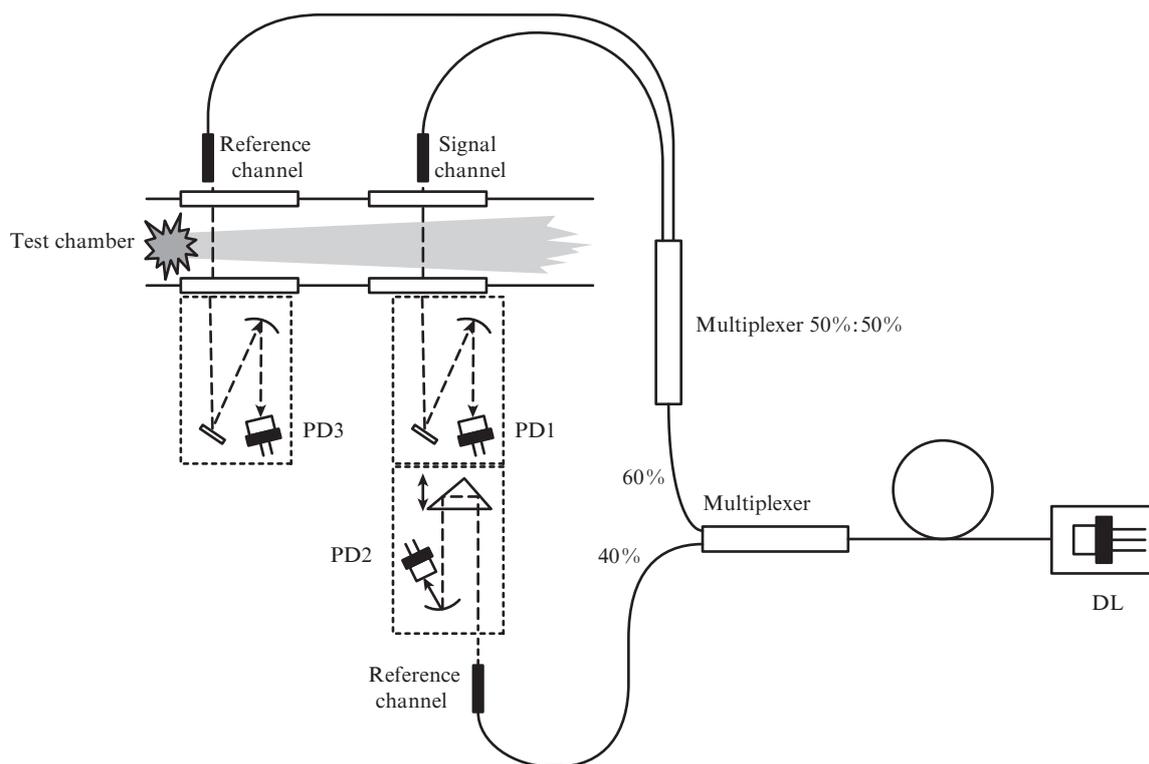


Figure 1. Optical scheme of the DLAS-spectrometer.

lenses, passes through the object under study and then is focused by spherical mirrors to the signal and reference photodiodes PD1 and PD3, respectively, placed in detection units on the opposite flange of the chamber.

As was mentioned, the difficulty in obtaining data about the spatial temperature profile in combustion zones is determined by substantial variations in the characteristics of the combustion process from run to run. This is related to stochastic processes of mixing the fuel with the oxidiser under direct injection from the wall, random character of plasma filament motion in a supersonic flow, and, as a consequence, considerable vibrations in flame front position. For obtaining the spatial temperature profile in various combustion zones it would be ideal to simultaneously (in a single run) probe various zones. This way, however, requires a much more complicated optical scheme, a system of data detection and processing, and makes the DLAS-spectrometer substantially more expensive.

In the present work, in a single run the average temperature along the optical path was determined at a single point of the two-dimensional (2D) profile (signal channel). The optical unit, which forms the probe beam on the input flange of the chamber, and the optical unit with a radiation detector at the output flange were mounted on two displacement systems and could synchronously move with an accuracy of 0.1 mm. This construction made it possible to align the axis of the probe beam with the optical axis of the detector unit once at the start of the experiment and this alignment was maintained in synchronous motion of both optical units, which provided plotting of the 2D temperature profile with no additional adjustment.

The reference channel introduced into the optical scheme allows for non-reproducibility of conditions in different runs. This channel is completely identical to the signal channel;

however, the position of the unit for DL beam formation on the input flange of the chamber and the position of the optical detector unit on the opposite flange are rigidly fixed. The whole procedure of data measurement, digitising and processing in the reference channel is completely identical to that in the detection unit. The main task of the reference channel was to discard the runs in which too large fluctuations of parameters (gas flow, volume of injected fuel, structure and intensity of igniting discharges) occur. In addition, at small deviations of the parameters from run to run the reference signals were used for normalising. In this way, non-reproducibility of the combustion process in various runs was substantially levelled.

A 2D temperature profile in the test volume was formed in a series of measurements under mechanical displacements of the detection channel from run to run. This method of measurements cannot record the profile in a single run but gives the possibility to match test results from different runs and to obtain information about the efficiency of the combustion process in various parts of the chamber. The experiments described in [10] lacked this possibility.

### 3.2. Differential scheme for accounting for external absorption (optical unit)

As was mentioned above, the hardly eliminable spacing of laboratory air in the path of the probe laser beam outside the signal chamber distorts the spectral profile of the absorption line and hinders the processing procedure. The FWHM of the water molecule absorption line at the frequency of  $7189.344\text{ cm}^{-1}$  inside the test chamber at a pressure of  $\sim 300$  Torr and temperature of 1000 K is  $\sim 0.03\text{ cm}^{-1}$ , and the corresponding FWHM of the same line at atmospheric pressure and room temperature is approximately thrice greater.

Thus, laboratory air strongly affects the detected absorption spectrum. In line fitting, it is difficult to take into account the external absorption because of the additional fitting parameters, uncontrolled moisture and temperature variations in laboratory air, and difficult determination of the optical path in the external arm.

For excluding the influence of atmospheric air, ballast sections are usually blown through with dry nitrogen or argon; nevertheless, residual water vapours cannot be removed in this way. The scheme of differential measurements substantially weakens the influence of ballast sections without blowing through them.

In the present work, signals were measured in a double-beam differential scheme with the signal and reference channels (see Fig. 1). The reference beam was collimated by a short-focus objective, reflected at an angle close to  $180^\circ$  by a moving prism, and focused by a spherical mirror to a differential PD2 detector. The entire optical unit of the reference channel was mounted near the chamber. Neither signal nor reference optical units were blown through with inert gas. The optical path length in the reference channel was taken equal to that in the signal channel by moving the reflecting prism. This optical unit decreased the contribution of atmospheric air outside the measurement cell into detected absorption spectra. Further reduction of this contribution will be discussed in Section 4.1.

### 3.3. Control and detection system

In the present work, similarly to [10], we used a distributed feedback diode laser (DFB NLK1E5GAA) operating in the range of  $1.39 \mu\text{m}$ . The laser radiation was extracted through a single-mode pigtail that was constructively connected with the semiconductor structure. In contrast to [10], an original digital system for control and data processing (SCDP) controlled the injection current and temperature of the DL, acquired, digitised and processed data.

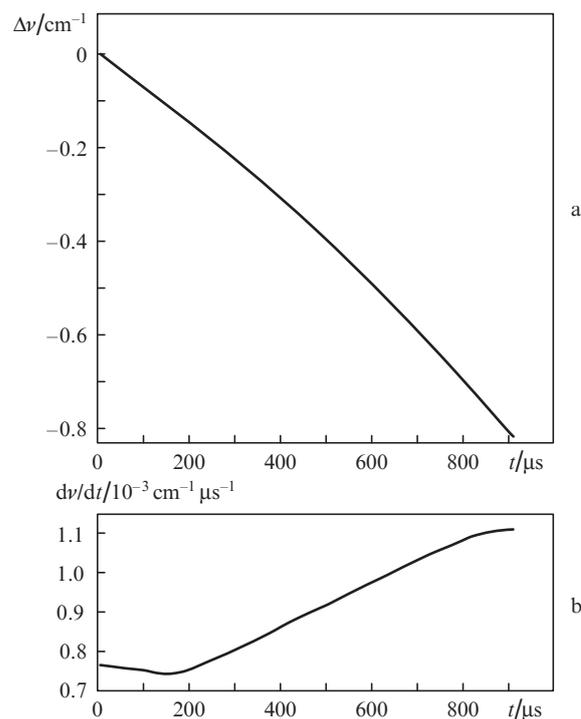
The developed SCDP is based on a multichannel input–output NI USB-6351 board [15]. The SCDP can vary temperature of the laser chip and stabilise it, as well as scan the DL radiation frequency by a digitally prescribed law.

Since the radiation wavelength of the DL depends on temperature, the normal operation of the device requires stabilisation of the chip temperature with the accuracy of no worse than  $0.001^\circ\text{C}$ . In the present modification of the DLAS spectrometer, a thermo-electric Peltier cooler combined with a thermistor was incorporated into the DL module. A proportional-plus-integral law of heating realised in the SCDP provided the temperature stability at the level of  $10^{-4}$  K in the range from 4 to  $50^\circ\text{C}$ . The inaccuracy of frequency tuning was  $2 \times 10^{-3} \text{ cm}^{-1}$  in 30 s after switching on the control system.

The diode laser was pumped by periodical trapezoidal current pulses. The radiation frequency was scanned due to a change in the laser crystal temperature under a pump current pulse. The pulse duration was  $910 \mu\text{s}$  and the pulse repetition rate was  $\sim 770$  Hz. The radiation frequency of the DL was fitted to the absolute frequency scale by detecting a water absorption spectrum in the reference cell at room temperature and at water vapour pressure of 10 Torr. The low pressure provided a small width of the absorption line, which enhanced the accuracy of determining the line centre. The detected lines were identified by using the HITRAN database [12].

The radiation frequency (wavelength) of the DL varies according to the time evolution (by the chosen law) of the

injection current. The instantaneous radiation frequency was tied to the wavelength scale by recording the transmission maxima of the Fabry–Perot interferometer with a free spectral range  $D^* = 0.0493 \text{ cm}^{-1}$ . By processing the fringe pattern recorded with DL scan in the chosen spectral range we have determined nonlinearity of the tuning characteristic, that is, nonlinearity of the radiation frequency dependence on time (injection current). Results of such processing are shown in Fig. 2. One can see that the rate of frequency variation is unsteady during the scanning. The corresponding data on the tuning DL characteristic have been recorded to a special file and were used for processing transient absorption spectra in real experiments.



**Figure 2.** Tuning characteristics of the DL under fast scanning by the injection current: (a) dependence of DL radiation frequency detuning ( $\Delta\nu$ ) from the initial value  $\nu_0$  at  $t = 0$  on the current scan time and (b) dependence of the frequency tuning rate on the current scan time.

At the SCDP switched on, the radiation frequency of the DL is repeatedly scanned by a chosen law within  $\sim 1 \text{ cm}^{-1}$ , and each scan lasts for approximately 1 ms. The external trigger starts signal recording from outputs of differential schemes in the measuring and reference channels and the direct signal from the measuring channel that is proportional to the current through the PD1 photodiode. The differential signals are actually absorption spectra in the measuring and reference channels with an added uncompensated spectrum of water outside the test chamber and possible base line variations. The direct signal in the measuring channel is necessary for controlling and measuring the intensity of passed laser radiation at every instant and is used for determining water concentration in the chamber. The NI USB-6351 board has a 16-bit ADC, which provides a substantially greater dynamic range of measured signals as compared to the 8-bit ADC of the Agilent 54621A oscilloscope employed in Ref. [10]. The sampling rate optimised for our problem was 512 kHz. The

time between successive scans was set to 1.3 ms. In this time interval 200 samples were taken (6.5  $\mu$ s per sample), and 140 from them were chosen for further processing. A single test run lasted for 500 ms; usually, most interesting regions were processed in the first 250 ms.

The program for controlling the DLAS spectrometer was realised in the graphical software package LabView 9.0 with the driver library NI 9.0 [16]. Note that the detection program operates in the wait and automatic recording regime. The external trigger signal starts spectra digitisation and recording for a prescribed time of the measuring cycle to the buffer of input–output NI USB-6351 board. After finishing the measuring cycle the data are transmitted from the buffer to a computer and are recorded to a hard disk. At the chosen parameters of time resolution and the duration of the entire measuring cycle (500 ms), the number of detected spectra is 380.

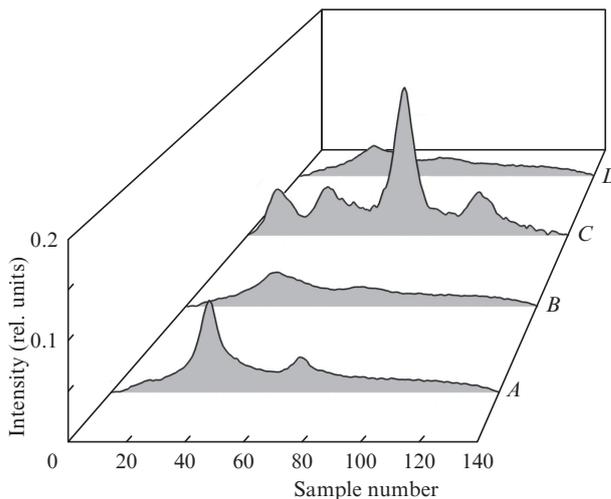
## 4. Results and discussion

### 4.1. Recording of transient absorption spectra

The new variant of the DLAS-spectrometer was used for studying the efficiency of the developed methods for plasma-assisted combustion on the IADT-50 facility. Similarly to the experiments described in [10], the measuring cycle had the following phases: 1) attaining the supersonic regime of the gas-dynamic facility (Mach number  $M = 2$ ), which usually takes about 100 ms; 2) switching on the electric discharge (after approximately 120 ms); 3) fuel injection into the test section and start of combustion; and 4) switching off the discharge (after approximately 190 ms), termination of combustion and fuel supply, and transfer to supersonic flow without combustion (end of cycle). The whole cycle takes approximately 500 ms, the most interesting part of the cycle, including the phases of attaining the supersonic regime, fuel injection and combustion, takes approximately 250 ms.

The procedure of primary processing of a series of detected transient spectra with digitising and storing in a PC memory is described in [10]. In Fig. 3 one can see spectra averaged over 30 DL frequency scans for every phase mentioned above. Specific features of variation in the gas mixture temperature averaged over the probe beam are clearly observed. In the spectrum *A* one can see the intensive ‘cold’ absorption line ( $\nu = 7189.344 \text{ cm}^{-1}$ ) and a weaker line ( $\nu = 7189.541 \text{ cm}^{-1}$ ). In this range the average temperature is not above 300 K.

In approximately 20 ms, the gas flow in the channel attains the supersonic regime; the static gas temperature in this case is  $T \approx 200 \text{ K}$ , which is substantially below room temperature. This results in freezing water vapours and after approximately 20–30 ms the intensities of both lines seen in spectrum *A* (Fig. 3) noticeably fall (spectrum *B*). In approximately 120 ms after the cycle starts on, the discharge is switched on and after  $\sim 20 \text{ ms}$  fuel injection occurs. At this instant the combustion process is initiated, which is accompanied by a fast temperature increase and origin of water vapours in the combustion zone. In spectrum *C* one can clearly see the absorption lines at the frequencies of 7189.200, 7189.541 and 7189.715  $\text{cm}^{-1}$ , which correspond to the transitions from levels that are higher than the lower level of the ‘cold’ line ( $\nu = 7189.344 \text{ cm}^{-1}$ ). The intensity of the latter became much lower. This character of the spectrum is kept for the whole combustion process (approximately 50 ms), then combustion vanishes and the



**Figure 3.** Transient spectra of water molecule absorption at various stages of combustion evolution: (*A*) initial stage, room temperature; (*B*) passing to a supersonic flow regime, freezing water vapours; (*C*) ignition, fuel injection, development of the combustion process; (*D*) termination of combustion, fast cooling of the gas in the supersonic flow.

‘hot’ lines disappear from the absorption spectrum, which is illustrated by spectrum *D*.

The scheme of differential detection described above substantially weakens the influence of laboratory air on the recorded absorption spectra in the chamber. However, this influence cannot be eliminated by only hardware means. The contribution of the path segment outside the chamber was further reduced by subtracting the spectrum of phase *B* with frozen water from spectra of phase *C*. Spectrum *B* comprises only absorption of atmospheric air outside the chamber. Hence, subtraction of this spectrum from the spectrum of the active phase, *C*, completely solves the problem of absorption outside the chamber in further processing.

### 4.2. Processing of spectra

In all works devoted to application of DLAS for diagnosing gas flows, temperature data are obtained by fitting the recorded spectra with those calculated from databases or measured experimentally at various temperatures and pressures under stationary conditions. In this case, either the ratios of integrated line intensities with noticeably differing lower levels, or the ratios of the line amplitudes are determined. In the present work we used two methods: fitting experimental data by simulated spectrum [17] and the correlation method of juxtaposing experimental data with simulated spectra. The latter, due to its calculation simplicity, may be easily incorporated into the program for spectra processing and provides actually online acquisition of the required data about the object temperature.

Assume that the detection system records and digitises  $N$  points corresponding to the intensity of light passed through the test object in a single scan. The detected absorption spectrum  $A_i$  will be presented by a set of such points. In the process of fitting [17] by the nonlinear least-squares method, spectrum  $B_i$  that is maximally close to the experimental absorption spectrum  $A_i$  is sought for. Spectrum  $B_i$  is simulated using information from databases. The dependence of experimental and simulated spectra on temperature and con-

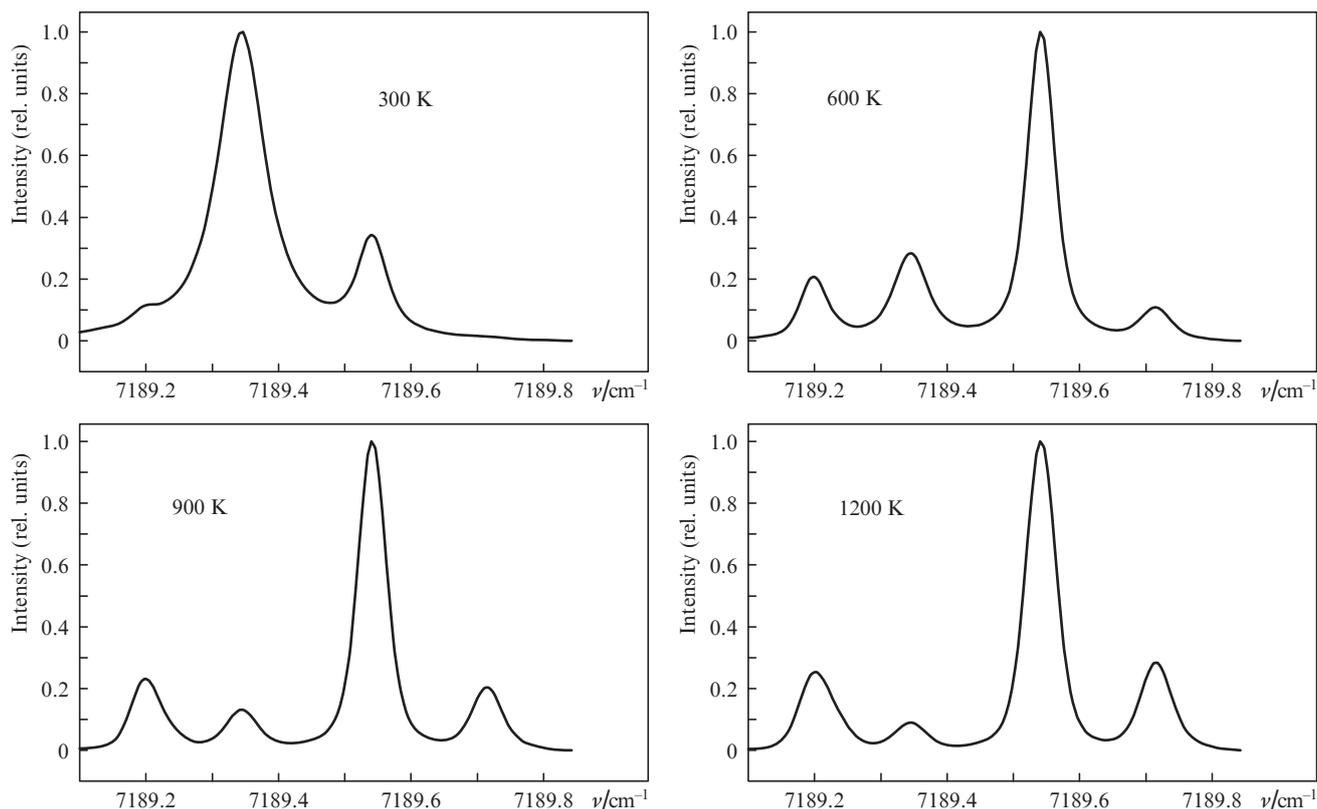


Figure 4. Spectra of water vapour absorption at four temperatures simulated with the data from databases.

centration of water vapour gives the possibility to find these parameters by fitting the experimental and simulated spectra.

The suggested correlation method implies calculation of the correlation function (coefficient) between the experimental spectrum  $A_i$  and a set of the simulated spectra  $B_i$  that have been calculated with a certain step ( $\Delta T = 20$  K) by using databases. Figure 4 illustrates four simulated spectra for various temperatures. Correlation functions for experimental spectra recorded in various combustion zones are presented in Fig. 5. The sought-for temperature of the test object is determined

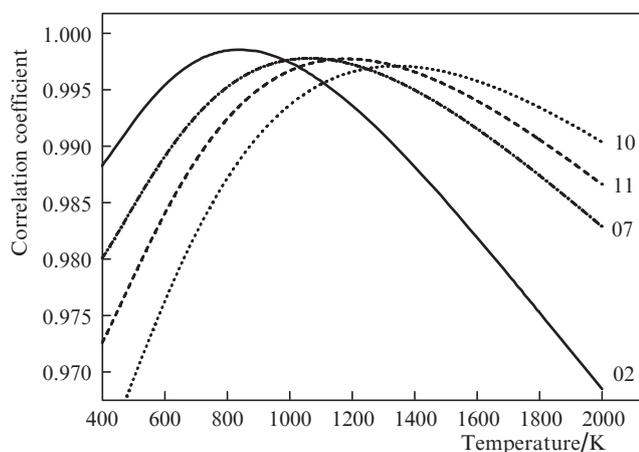


Figure 5. Correlation functions of four experimental spectra recorded at various temperatures. Numerals on the right denote the number of the test run according to Table 1. The maxima of functions correspond to (02) 868, (07) 1062, (11) 1181 and (10) 1341 K.

from the maximum correlation between a simulated spectrum  $B_i$  and an experimental spectrum  $A_i$ .

Spectra recorded in different test runs and different combustion zones have been processed according to the both algorithms – by fitting to simulated spectra and by the correlation method. The temperature was found from the ratio of integrated intensities of lines with  $\nu = 7189.541$  and lines with  $\nu = 7189.715$   $\text{cm}^{-1}$ . Results of processing are given in Table 1. One can see that both algorithms yield data that well agree in temperature. The correlation method was realised in real time (online) regime, so that the values of  $T$  were accessible immediately after stopping the measurement. Fitting by the simulated spectrum required certain time for primary processing of experimental spectra and was realised offline.

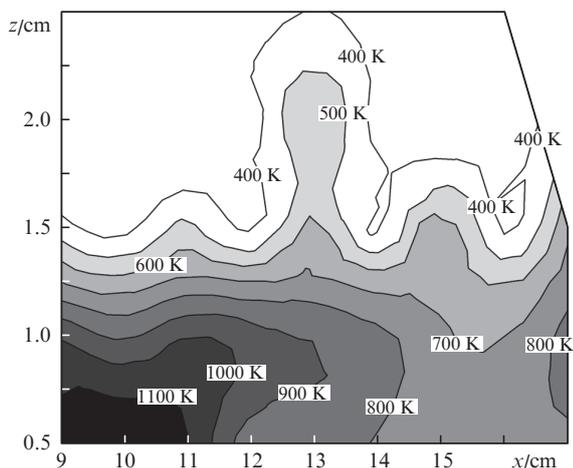
Table 1. Results of measuring temperature by various methods.

Number of test run	Temperature/K	
	Fitting by simulated spectrum	Correlation approach
02	858	868
03	836	838
06	1084	1097
07	1061	1062
10	1378	1341
11	1167	1181

#### 4.3. Measurement of the spatial temperature profile in the test chamber

The two-dimensional (along and across the axis of gas flow propagation) temperature profile was measured on the IADT-50 test combustor by using the improved variant of the

spectrometer. In modelling the profile, both optical units on two flanges of the chamber moved synchronously. The motion step was 1 cm in the direction of the gas flow and 0.5 cm in the perpendicular direction ( $z$  axis). Each profile point corresponded to a single run. If the parameters of a test run strongly deviated from normal values (it was verified by the reference channel) then the test repeated. Temperature values obtained in the result of processing separate points of the 2D-profile were subjected to smoothing. A ‘map’ of the temperature distribution obtained in this way is presented in Fig. 6. The first point in the figure with the coordinates (9, 0.5) is situated at a distance of 9 cm from the initiating electrodes along the flow and is shifted by 0.5 cm in the direction normal to the wall of chamber with electrodes. In this series of experiments ethylene was used as a fuel. One can see that the maximal temperature is ‘pressed’ to the domain of electric discharges and sufficiently rapidly falls in the direction normal to the wall with electrodes. The temperature also falls in the direction of the gas flow, but, not so rapidly. The results of this experimental series yielded valuable information for improving the design of the combustion chamber.



**Figure 6.** 2D-profile of temperature in a hot zone. The origin of coordinates (9, 0.5) is at a distance of 9 cm from igniting electrodes and 0.5 cm above the wall of the chamber with electrodes.

#### 4.4. Ways of improving the method

The DLAS method in its most popular variant is used for determining an average temperature along a probe beam. In both processing algorithms used in the present work (spectrum fitting and construction of the correlation function), the varied parameter is the temperature that is constant along the entire optical path. In real experiments the combustion zone of mixing flows is essentially heterogeneous in all three coordinates. In the experimental IADT-50 chamber the combustion zone formed near electrodes and near the point of fuel injection propagates along the flow, expanding and occupying the entire volume of chamber. Obviously, the model of the temperature that is uniform along the beam substantially understates the calculated ‘average’ temperature in a hot nucleus. This difference between the ‘average’ temperature calculated by spectra and the maximal temperature in the chamber reduces as the hot zone expands in the direction of the gas flow, and the flow is cooled.

There are various approaches to solve the problem of determining temperature if the latter is not uniformly distributed. The most radical is employment of tomography probing where a set of diode laser beams crosses the test object in various directions [6–8]. This approach noticeably complicates and makes more expensive both the optical scheme and the system of data acquisition and processing.

In our case the design of the test chamber does not imply probing the gas volume in different directions; one possible solution may be to take *a priori* a certain law for the temperature distribution along  $z$  coordinate, for example, it may be Gaussian, triangle or trapezoidal distribution. The latter variant may adequately describe the model of a cold near-boundary gas layer adjacent to chamber windows. In this case, additional variation of the parameters arise in the fitting algorithm (for example, the width of Gaussian distribution), which require a greater number of detected absorption lines. In our case the problem can be solved by extending the spectral ranges in which several water absorption lines with substantially different lower levels of the transition can be detected. These possibilities are open when diode lasers with wide tuning ranges are used [18, 19]. Another approach is related with the characteristic profile of the gas temperature obtained in the result of gas-dynamic modelling of supersonic combustion with several fuel injectors as was done in [20].

## 5. Conclusions

A new version of an absorption spectrometer with diode lasers is developed for measuring temperature and concentration of water vapours in combustion zones of mixing fuel and oxidiser supersonic flows. For the first time, a two-dimensional temperature distribution in a hot zone was obtained by DLAS under the conditions of single test runs under considerable variations of the gas mixture parameters. For realising this approach, the main spectrometer units have been substantially upgraded: 1) stability and reproducibility of diode laser parameters (chip temperature, reproducibility of the scanning range, long-term tuning characteristic) have been improved; 2) the dynamic range of the detection system has been extended (to 16 bit); 3) a reference channel has been introduced for taking into account absorption of water vapour outside the cell; 4) exact (to 0.1 mm) synchronous motion has been realised for the driving and detection optical units which provided coincidence of the optical axis of the probe beam with that of the detection optical unit; and 5) the reference channel has been introduced which allows one to discard failure runs with too large fluctuations of parameters in the combustion zone and to ‘sew’ the results of different successful test runs by normalising the line intensities in the signal channel to the intensities of corresponding lines in the reference channel.

A new algorithm has been suggested for obtaining information about the mixture temperature by constructing the correlation function for an experimental spectrum and spectra simulated with data from databases. Results of temperature measurements obtained with the correlation algorithm well agree with the results of fitted spectra. The suggested correlation method was incorporated into the software for data processing so that an operator obtains temperature data from the probe zone of the gas mixture in real time. Note that the correlation method suggested was realised by using independent data on the mixture pressure. The stability of the method with respect to variations in principal parameters (mixture

pressure, concentration of water vapour and baseline variations) will be investigated in the future.

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